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by

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ABSTRACT

This is the Final Report for O. N. R. Contract Number N00014-86-K-0129. It summarizes research results and lists publications, presentations, and students who performed O. N. R. research.

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INTRODUCTION

This Final Report summarizes progress under Office of Naval Research Contract Number N00014-86-K-0129 between 16 January 1986 and 15 January 1991. Professors William L. Siegmann and Melvin J. Jacobson were Co-Principal Investigators during this period, with Professor John S. Robertson serving as Co-Principal Investigator for a portion of the time. The average contract support during the five-year period was about $74,600 annually.

Section I abstracts our research in six general categories: (1) Shallow Water Acoustics, (2) Ocean Current Effects, (3) Tracking Algorithms, (4) Three-Dimensional Parabolic Approximations, (5) Sound Speed/Density Modeling, and (6) Computational Acoustics. Twenty publications are listed chronologically in Section II. Twenty-four presentations during the Contract period are listed chronologically in Section III. Finally, Section IV gives the names of ten graduates students who worked on ONR research and received Rensselaer degrees.

I. RESEARCH SUMMARY

(1) Shallow Water Acoustics

Effects of horizontal stochastic bottom structure on acoustic intensity in an isospeed ocean have been studied previously [J. Acoust. Soc. Am. **76**, 1445-1455 (1984)]. The bottom density and sound speed were taken to be random and ray theory was used. In this study[2] we add a rough water-bottom interface, consisting of large scale, two-dimensional random facets upon which small scale roughness may be superimposed. Each facet is assumed to possess small random depth deviation, slope, and curvature. Initially, we take acoustic rays to be specularly reflected from the facet bottom, and derive expressions for the mean and variance of incoherent intensity at a point receiver for a transmitted cw signal. The results are sufficiently general to permit their use with different bottom-acoustic models, but we employ Mackenzie theory here. Relative effects of structure and topography are compared. Subsequently, small scale roughness is superimposed on the facets, and the added consequences of scattering are considered.

The influence on ray propagation of including both attenuation and beam displacement at the bottom of a shallow-water isospeed channel is determined.[6] Attenuation is incorporated using the Mackenzie bottom model, rather than the commonly used Rayleigh reflection theory. Properties of displacement are studied as a function of launch angle and parameters such as bottom-to-water density, channel depth in wavelengths, and channel aspect ratio. Differences in beam displacement for the two bottom models are shown to affect the number and geometry of rays between surfaced source and receiver. Formulas for per ray amplitude and phase shift and for incoherent total field intensity are developed. Comparisons are made between these quantities for both modified and classical ray theory with a Mackenzie bottom, and also for both Mackenzie and Rayleigh bottom models using modified rays. Numerical computations show significant phase and amplitude differences arising in both types of comparisons.

In Reference 8, a modified ray theory is used to study the effects on acoustic intensity of randomness in bottom structure. A shallow isospeed ocean channel with horizontal boundaries is assumed. The randomness is produced by stochastic variations in the bottom density and sound speed in the horizontal direction beneath the water-bottom interface. Beam and time displacements at the ocean bottom are incorporated into each acoustic ray. Ray geometry, spreading loss, and bottom loss are analyzed in order to obtain expressions for the mean and variance of intensity at

a point receiver for a transmitted cw signal. Formulas are sufficiently general to permit their use with different bottom acoustic models of sound reflection. In order to incorporate bottom attenuation simply, Mackenzie theory is employed here. The distinctive acoustic consequences of bottoms of different density mean and horizontal correlation are discussed. In addition, comparisons of results using the modified ray theory and standard ray theory are provided. Also, intensity moments are described for differing source-receiver range, water depth, and acoustic frequency.

(2) Ocean Current Effects

In a previous article [J. Acoust. Soc. Am. **77**, 1768-1780 (1985)], the authors developed a family of parabolic equations that includes effects due to the presence of a time dependent, depth dependent current. Some of these equations contain a new term that explicitly depends on current gradient. In Reference 5, certain effects of this new term are studied. By transforming the parabolic equations, it is possible to convert them to forms that can be directly solved numerically using existing implementations. Ocean currents with vertical fine structure present situations that can require these new types of parabolic approximations. Propagation in a shallow isospeed channel is examined, with both rigid and lossy bottoms, and use is made of a shear flow with features of an actual ocean current. The vertical current variation can cause changes in relative intensity that are substantial and that depend on bottom loss, source and receiver locations, and acoustic frequency. Intensity differences are demonstrated and examined for reciprocal sound transmissions.

Ocean currents can cause significant and interesting effects on the intensity of underwater sound transmissions. We study this phenomenon via the parabolic approximation, beginning with conservation laws.[3] The derivation of a family of equations, each of which is valid for different magnitudes of current speed, current gradient, and sound-speed variation, is discussed. Numerical results indicate that some current structures can cause large variations in received intensity, and that substantial differences can occur in reciprocal transmissions. Current effects on intensity may be quite sensitive to the sound speed distribution, including its range dependence.

A parabolic approximation to the acoustic propagation equations in a uniformly moving underwater channel is derived, with the intent of investigating current effects.[4] A model is developed from the basic fluid equations for acoustic pressure in the presence of a uniform horizontal current. Sound speed variations in

both range and depth are permitted. Further approximations are applied and justified to yield a two-dimensional parabolic equation like that most widely implemented numerically. It is shown that uniform currents are manifested as a shift in the reference sound speed, which enables current incorporation in already existing algorithms. Boundary conditions and an initial condition are investigated for possible current dependence. For sound speed profiles with independent depth and range variations, analytic formulas are presented for the ratio of intensity with and without currents. Examination of this ratio for the case when the sound speed is depth independent shows that currents can indeed have substantial effects on intensity. Numerical calculations from an implicit finite difference program illustrate effects on relative intensity of even fairly small uniform currents.

The influence of random, horizontal, depth dependent ocean currents in the parabolic approximation is studied.[9] The current is taken to have a depth dependent mean, upon which is superimposed a small fluctuating component. Emphasis is placed on received acoustic intensity. Recently derived parabolic equations including currents are examined using asymptotic and numerical methods. Expressions are derived for the mean and standard deviation of intensity. The fluctuating current component is taken as having an exponential-cosine autocorrelation function with depth, although other functions could be used. Formulas obtained are sufficiently general to permit many types of depth dependent sound speeds and bottom interface models. Current fluctuation effects on intensity moments are illustrated for the specific case of an isospeed channel with a perfectly hard bottom. The acoustic consequences of changes in physical parameters directly related to current fluctuations, such as its standard deviation and correlation length, are discussed. Also exhibited are changes in random current effects on intensity that result from changes in noncurrent related parameters, such as acoustic frequency and channel depth.

(3) Tracking Algorithms

The sensitivity of a passive horizontal tracking algorithm to variations in input measurements is investigated in Reference 1. The algorithm determines estimates for depth, range, bearing, horizontal speed, course, and frequency for a cw acoustic source moving with constant velocity at fixed depth. The receiver is a horizontal linear array towed at a constant depth. Both source and receiver move in the upper portion of a deep ocean and are separated by a relatively short range. Dominant acoustic signals are presumed to arrive along two upper ocean ray paths. The

algorithm uses a new combination of input quantities, including multipath information, Doppler frequency shifts, and array directional measurements. Procedures are developed for analyzing effects of input measurement errors on source localization. The robustness of the algorithm to small variations in acoustic measurements and environmental parameters is demonstrated for a variety of source-receiver configurations. Variance estimates of position and motion are obtained in terms of input-measurement variances. Bounds on tracker performance are developed for measurements that are affected by noise. Results from the several types of analyses corroborate the sensitivity characteristics of the algorithm.

The behavior of incoherent total field intensity is considered[11] for a moving cw source in shallow water. The ocean channel is assumed isospeed, with a planar perfectly reflecting surface and planar lossy bottom. The source moves on a linear path at constant depth, and the receiver is fixed on the bottom. An expression for incoherent total field intensity loss is derived in terms of source motion and environmental parameters. For a bottom with uniform loss per ray reflection, special functions are used to develop and analyze an approximation for intensity. The behavior of this novel approximation with respect to variations in source quantities, such as range, depth, and speed, as well as bottom loss variations, suggests its possible application in source motion prediction. Two properties of the approximation, peak curvature and peak width of intensity versus time, are selected as source motion descriptors. Both are shown to be relatively insensitive to bottom loss variations, but sensitive to changes in source quantities. Descriptors are applied to an example, and their possible use in supplementing existing passive tracking methods is discussed.

(4) Three-Dimensional Parabolic Approximations

Several parabolic-type approximations have been developed for single frequency, three-dimensional underwater acoustic propagation. One wide angle three-dimensional equation has been solved efficiently by finite difference techniques. In Reference 7, accuracy of this new algorithm is indicated by comparison of computational results with analytic solutions. Sensitivity of results to variations in step sizes is discussed. Computations suggest the types of three-dimensional propagation effects which can be produced. An example is provided of the capabilities of the method for sound propagation through ocean features, such as a frontal zone, which can vary in three dimensions.

A family of closed form mathematical expressions has been constructed for use in examining how propagation models treat energy exchange between vertical azimuthal planes.[20] The general need for such solutions has been pointed out in recent professional meetings and workshops. One specific purpose of developing these expressions was to test a model which solves a high order, three-dimensional, wide angle parabolic-type wave equation. Expressions from the family solve exactly either narrow or wide angle parabolic approximations for particular indices of refraction that vary in radial and azimuthal directions. Consequently, they are appropriate for accuracy and capability testing of parabolic approximation algorithms. The formulas are of novel type, and cannot be obtained by the classical method of separation of variables. The expressions are valid for propagation over a range of frequencies and without backscattering, so they are available for comparison tests with propagation models of either ray or other wave types.

The effect of a steady, depth dependent, horizontal shear current in an underwater sound channel is considered.[15] Because the source-receiver direction and current direction need not lie in the same vertical plane, the propagation problem is inherently three dimensional. A three-dimensional parabolic approximation for this channel is formulated by extending a two-dimensional result obtained previously.[5] It is shown that, if the azimuthal derivatives are small enough to be neglected in the farfield, azimuthal effects appear only as coefficients in the parabolic equation. Therefore, an $N \times 2$-D technique can be used to solve the parabolic equation. Numerical examples are used to examine cross current propagation. It is shown that substantial intensity variations can occur as the angle between the source-receiver direction and current varies.

(5) <u>Sound Speed/Density Modeling</u>

Range dependent extensions to Munk's canonical deep water sound speed profile are discussed.[16] A formalism is presented which ensures that the main properties of the profile are preserved even as the profile changes from place to place in the ocean. These extensions permit one way to formulate relatively simple analytical expressions for these profiles that can be useful as inputs to propagation models.

An exact expression for the isothermal sound speed in seawater is obtained from an internationally accepted equation of state.[17] This derived sound speed expression offers certain practical and theoretical advantages over empirical formulations encountered elsewhere in the literature. For example, as physical

properties of seawater are obtained to increased accuracy, adjustments in the coefficients are easily made. Also, the exact expression provides a standard against which other models for seawater sound speed can be judged. Procedures for obtaining practical sound speed profile approximations from the new expression are described.

A class of depth dependent density profiles is described[12] that permits the construction of analytical solutions to a variable density parabolic equation. These solutions can serve as accuracy benchmarks for numerical algorithms that solve such equations.

(6) Computational Acoustics

The parabolic approximation method is widely recognized as useful for accurately analyzing and predicting sound transmission intensity in diverse ocean environments. One reason for its attractiveness is that solutions are marched in range, thereby avoiding the large internal storage requirements when using the full wave equation. Present finite difference implementations employ a range step size that is prescribed by either the user or the code and that remains fixed for the duration of the computation. An algorithm is presented in which the range step is adaptively selected by a procedure within a version of an implicit finite difference implementation of the parabolic approximation.[14] An error indicator is computed at each range step, and its value is compared to an error tolerance window that is readily specified by the user. If the error indicator falls outside this window, a new range step size is computed and used until the error indicator again leaves the tolerance window. Furthermore, for a given tolerance, this algorithm generates a range step size that is optimal in a specified sense and that often leads to large decreases in run time. Additional related modifications to the implementations are discussed. Several examples are presented that illustrate the efficacy of the enhanced algorithm.

Substantial improvements in the efficiency of finite difference implementations for numerically solving parabolic equations can be achieved via adaptive selection of mesh dimensions. For example, we have developed and reported an algorithm[14] which adaptively selects range step sizes based on the behavior of an easily computed error indicator. Gains in computational efficiency were demonstrated for a variety of propagation environments. Reference 19 presents new work which significantly extends these results. A related error indicator that depends on depth discretization is developed, and an adaptive

algorithm is formulated with this indicator. This permits the implementation of depth mesh refinement strategies. Numerical examples demonstrating the performance of this algorithm are presented and discussed.

Many mechanisms can be responsible for fluctuations of sound intensity and phase through the atmosphere over the Earth's surface. In Reference 18, the effect of wind gusts on received intensity at short range is examined. Using a parabolic approximation, relative intensity for a continuous wave (cw) omnidirectional source is calculated using the effective sound speed profiles obtained from meteorological data. Two characteristic scale thicknesses are used to model the wind gust profiles. The thinner layer thickness can result in temporal intensity fluctuations as high as 10 dB. It is emphasized that these fluctuations are refractive and deterministic. In an actual experiment, these fluctuations would be detected along with additional variations caused by wind noise turbulent scattering.

A modified wide angle parabolic equation is studied for a uniform plane-parallel waveguide with pressure release surface and rigid bottom.[10] In this situation, the equation is separable, and the resulting fourth-order boundary value problem is obtained and solved, which leads to a new exact solution. It is shown that the depth dependent eigenfunctions in this instance are identical to those resulting from both the standard parabolic equation and Helmholtz equation in the same channel. Modal wavenumbers are shown to be equivalent to the first three terms of the Taylor expansion for the Helmholtz wavenumbers, which is better than for the standard PE wavenumbers. This exact solution can serve as an accuracy benchmark for numerical implementations.

A three way scheme for classifying the nature and intended purpose of benchmark problems in computational ocean acoustics is proposed in Reference 13. This scheme resolves some ambiguities that have crept into the literature. Specifically, benchmark problems should provide ways to determine: (1) the absolute accuracy of the numerical model; (2) how accurately the numerical model performs relative to other models; and (3) the speed of the numerical model compared to others. This scheme is designed to aid researchers in gauging the utility of benchmarks, as new test problems are introduced.

II. PUBLICATIONS

1. "Sensitivity of a Passive Tracking Algorithm to Input Variations," J. Acoust. Soc. Am. **79**, 644-656 (1986).

2. "Random-Bottom Structural and Topographical Effects on Sound Transmission in a Shallow Channel," J. Acoust. Soc. Am. **81**, 650-659 (1987).

3. "On the Calculation of Acoustic Intensity Fluctuations Caused by Ocean Currents," Progress in Underwater Acoustics, Plenum, New York, 411-418 (1987).

4. "Effects of Uniform Horizontal Currents in the Parabolic Approximation," J. Acoust. Soc. Am. **82**, 545-558 (1987).

5. "Acoustical Effects of Ocean Current Shear Structures in the Parabolic Approximation," J. Acoust. Soc. Am. **82**, 559-573 (1987).

6. "Effects of Bottom Attenuation on Acoustic Propagation with a Modified Ray Theory," J. Acoust. Soc. Am. **82**, 1741-1751 (1987).

7. "Finite Difference Computations of Three-Dimensional Sound Propagation," Computational Acoustics: Wave Propagation, Elsevier, New York, 91-109 (1988).

8. "Random-Bottom Structural Effects on Shallow-Water Sound Transmission Using a Modified Ray Theory," J. Acoust. Soc. Am. **83**, 2097-2107 (1988).

9. "Sound Propagation Through Random Currents Using Parabolic Approximations," J. Acoust. Soc. Am. **84**, 1765-1776 (1988).

10. "An Exact Solution to a Modified Wide-Angle Parabolic Equation," J. Acoust. Soc. Am. **84**, 1791-1793 (1988).

11. "An Intensity Approximation for Source Motion in Shallow Water, with Applications to Passive Tracking," J. Acoust. Soc. Am. **85**, 90-103 (1989).

12. "A Class of Density Profiles for Constructing Analytical Solutions to a Variable-Density Parabolic Equation," J. Acoust. Soc. Am. **85**, 2661-2662 (1989).

13. "A Classification Scheme for Computational Ocean Acoustic Benchmark Problems," Applied Acoustics **27**, 65-68 (1989).

14. "An Efficient Enhancement of Finite-Difference Implementations for Solving Parabolic Approximations," J. Acoust. Soc. Am. **86**, 252-260 (1989).

15. "A Treatment of Three-Dimensional Underwater Acoustic Propagation Through a Steady Shear Flow," J. Acoust. Soc. Am. **86**, 1484-1489 (1989).

16. "Range-Dependent Extensions to Munk's Canonical Sound-Speed Profile," J. Acoust. Soc. Am. **86**, 2454-2456 (1989).

17. "A Standard Equation for the Speed of Sound in Seawater," Applied Acoustics **29**, 247-252 (1990).

18. "Numerical Simulation of Intensity Fluctuations Caused by Wind Gusts," J. Acoust. Soc. Am. **87**, 1353-1355 (1990).

19. "Adaptive Numerical Enhancements to Finite-Difference Algorithms for Parabolic Approximations," Computational Acoustics: Ocean-Acoustic Models and Supercomputing, North-Holland, Amsterdam, 101-113 (1990).

20. "Analytical Solutions for Testing Accuracy and Azimuthal Coupling in Three-Dimensional Acoustic Propagation," Computational Acoustics: Ocean-Acoustic Models and Supercomputing, North-Holland, Amsterdam, 129-142 (1990).

III. PRESENTATIONS

1. "Transmission Intensity in Shallow Oceans, and Implications for Passive Tracking," 111th Meeting of the Acoustical Society of America, May 1986.
2. "On the Calculation of Acoustic Intensity Fluctuations Caused by Ocean Currents," Underwater Acoustics Symposium, XII International Congress of Acoustics, July 1986.
3. "Computations of Three-Dimensional Sound Propagation in the Ocean," Yale University, August 1986.
4. "Sound Propagation Through Random Currents Using Parabolic Approximations," 112th Meeting of the Acoustical Society of America, December 1986.
5. "Sound Propagation in Three Dimensions Using a New Numerical Algorithm," 112th Meeting of the Acoustical Society of America, December 1986.
6. "Three-Dimensional Parabolic Approximations for Acoustic Propagation," University of Rochester, February 1987.
7. "Three-Dimensional Parabolic Approximations and Environmental Acoustics," Naval Ocean Research and Development Activity, June 1987.
8. "Parabolic Approximations for Acoustic Propagation," Harvard University, June 1987.
9. "An Efficient Enhancement of Finite Difference Implementations for Solving Parabolic Equations," 114th Meeting of the Acoustical Society of America, November 1987.
10. "Three-Dimensional Underwater Acoustic Propagation Through a Steady Shear Flow," 114th Meeting of the Acoustical Society of America, November 1987.
11. "Mathematical Modeling of Acoustic Wave Propagation by Parabolic Approximations," United States Military Academy, November 1987.
12. "Applications of Adaptive Methods to the Parabolic Equation Method in Underwater Acoustics," Naval Underwater Systems Center, New London and Newport, January 1988.
13. "Mathematical Modeling of Sound Propagation in the Atmosphere Using Parabolic Approximations, " 6th ARO Conference on Applied Mathematics, March 1988.
14. "Computational Results Using FOR3D and an Analytic Eddy Model," 116th Meeting of the Acoustical Society, November 1988.
15. "Interfacing Mesoscale Ocean Prediction and Parabolic Acoustic Propagation Models," 2nd IMACS Symposium on Computational Acoustics, March 1989.
16. "Analytical Solutions for Testing Accuracy and Azimuthal Coupling in Three-Dimensional Acoustic Propagation," 2nd IMACS Symposium on Computational Acoustics, March 1989.

17. "Adaptive Numerical Enhancement to Finite-Difference Algorithms for Parabolic Approximations," 2nd IMACS Symposium on Computational Acoustics, March 1989.

18. "A Modified k_0-Independent Parabolic Equation Incorporating Range Refraction," 117th Meeting of the Acoustical Society of America, May 1989.

19. "Effects of Random-Bottom Topography on the Parabolic-Approximation Determination of Acoustic Intensity," 117th Meeting of the Acoustical Society of America, May 1989.

20. "Modeling Acoustic Effects of Ocean Currents with the Parabolic Approximation," Raytheon Corporation, June 1989.

21. "Ocean-Acoustic Model Interfacing Sensitivities," Harvard University, April 1990.

22. "A Three-Dimensional Time-Domain Paraxial Approximation for Underwater Acoustic Wave Propagation," 119th Meeting of the Acoustical Society of America, May 1990.

23. "Environmental Sensitivity in Ocean-Acoustic Interfacing," NATO Conference on Ocean Variability and Acoustic Propagation, June 1990.

24. "A New Model for Marching Computation of Ocean Acoustic Backscatter," 120th Meeting of the Acoustical Society of America, November 1990.

IV. GRADUATE STUDENTS PERFORMING ONR RESEARCH

1. Berend Tober, Master of Science, May 1986.
2. Laurie Law, Master of Science, May 1986.
3. William Konya, Master of Science, August 1986.
4. John S. Robertson, Doctor of Philosophy, December 1986.
5. Charles E. Ashley, Doctor of Philosophy, December 1986.
6. Doris Azarcon, Master of Science, May 1987.
7. Ronald I. Brent, Doctor of Philosophy, December 1987.
8. Iman Schurman, Master of Science, May 1988.
9. Carol Driggs, Master of Science, August 1989.
10. Kevin Bongiovanni, Master of Science, August 1990.

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